Computerized photo-plethysmography of the finger

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A microcomputer system for studying photo-plethysmography of the finger (PPF) was designed and applied to 50 non-premedicated healthy boys (one to ten years old) undergoing general anaesthesia (halothane in 70% N_2O, with mechanical ventilation) for outpatient inguinal hernia repair. The purpose of this study was to assess the accuracy of computerized estimations of the photo-plethysmographic (arterial waves) amplitude and to evaluate whether or not PPF allows discrimination between two different surgical stimuli (skin incision, and manipulation of the spermatic cord). When anaesthesia was stable for at least five minutes (end-tidal halothane = 1.25–1.5%; $P_{ET}CO_2$ = 32–38 mmHg; $SpO_2 \geq 98\%$; rectal temperature = 36.3–37°C; ambient operating room temperature = 20–21°C), and immediately before the skin incision, computerized estimations of the photo-plethysmographic (arterial waves) amplitudes (PPA) were recorded and saved for later comparison with direct (manual) measurements of the plethysmographic tracing, using an arbitrary scale of 0–255 units. Also, the values of PPA, systolic blood pressure, and pulse rate recorded immediately before the skin incision were later compared with the maximum changes in these same values recorded 30–90 sec after skin incision, and 30–90 sec after manipulation (traction + dissection) of the spermatic cord. Six boys (three to ten years old) stayed quiet enough, during induction of anaesthesia by mask, to allow regression analysis of PPA, systolic blood pressure, and pulse rate (Y) on end-tidal halothane/70% N_2O (X). Computerized estimations tended to give a higher reading, by between 0.2 to 0.8 units, than direct measurements. Spearman and Kendall corrrelations showed that computerized and direct measurements were associated ($P < 0.0001$), the Kolmogorov-Smirnov's test revealed that the two distributions were identical ($P = 1$), the mean difference between computerized and direct estimations of the PPA was 0.52 ± 1.08 units, and the limits of agreement (–1.6 and 2.6 units) were small enough to be confident that computerized (automatic) estimations of PPA can be used for clinical purposes. Skin incision caused a smaller decrease of PPA (24%) than manipulation of the spermatic cord (37%). Changes in PPA were more pronounced than changes in systolic blood pressure or pulse rate ($P < 0.05$). Linear regressions and Fisher's exact test (two-tailed) showed that, during induction of anaesthesia with halothane in 70% N_2O by mask ($n = 6$), changes in end-tidal halothane concentration were related more to changes in PPA than to changes in systolic blood pressure and/or in pulse rate ($P < 0.05$). In conclusion, computerized PPF allows discrimination between two different surgical stimuli, provides quantification of the sympathetic response to preoperative anxiety, and may be useful for studying pre-anaesthetic sedation.

Les auteurs décrivent un système informatisé qui permet d'étudier la photo-pléthysmographie digitale (PPD) et l'utilisent chez 50 garçons (de un à dix ans; stade physique I de la classification ASA; non-prémédiqués) ayant été anesthésiés (avec de l'halothane dans 70% N_2O, sous respiration mécanique) pour herniotomie inguinale en régime ambulatoire. Le but de cette étude était de déterminer l'exactitude des valeurs de l'amplitude photo-pléthysmographique (ondes artérielles) calculées par l'ordinateur et d'évaluer dans quelle mesure la PPD permet de distinguer la réaction sympathique à deux stimuli chirurgicaux différents (incision de la peau et manipulation du cordon spermatique). Lorsque l'anesthésie était stable pendant au moins cinq minutes (halothane alvéolaire = 1,25–1,5%; CO_2 alvéolaire = 32–38 mmHg; $SpO_2 \geq 98\%$; température rectale = 36,3–37°C; température de la salle d'opérations = 20–21°C), et immédiatement avant l'incision de la peau, on a enregistré les valeurs des amplitudes photo-pléthysmographiques (APP) calculées par l'ordinateur et, ultérieurement, ces amplitudes ont été comparées avec les mêmes amplitudes mesurées directement sur le tracé pléthysmographique. Une échelle arbitraire, de 0–255 unités, fut utilisée. D'autre part, les valeurs de l'APP, de la pression artérielle systolique et de la fréquence du pouls enregistrées immédiatement avant l'incision de la peau furent comparées avec les mêmes valeurs obtenues 30–90 sec après

Key words
ANAESTHESIA: paediatric;
COMPUTERS, MEASUREMENT TECHNIQUES: plethysmography;
MONITORING: blood flow.

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Accepted for publication 31st August, 1992.

l'incision de la peau et avec celles qui ont été enregistrées 30–90 sec après la manipulation (traction + dissection) du cordon spermatique. Six enfants (de trois à dix ans) sont restés suffisamment immobiles, pendant l'induction de l'anesthésie au masque, pour permettre d'étudier la régression de l'APP, de la pression artérielle systolique et de la fréquence du pouls (Y) sur les concentrations alvéolaires d'halothane/70% N_2O (X). Les calculs de l'APP faits par l'ordinateur tendaient à donner des lectures plus élevées, de 0,2 à 0,8 unités, que celles éffectuées manuellement à partir de pléthysmogrammes imprimés. Les corrélations de Spearman et de Kendall ont montré que les deux types de mesures étaient associés ($P < 0{,}0001$), le test de Kolmogorov-Smirnov a confirmé que les deux distributions étaient identiques ($P = 1$), la différence moyenne entre lectures informatisées et lectures directes (manuelles) était de 0,52 ± 1,08 unités, et les limites de concordance (–1,6 et 2,6 unités) étaient suffisamment petites pour confirmer que les lectures par ordinateur peuvent être employées à des fins cliniques. L'incision de la peau produisit une diminution significative de l'APP (24%); cette diminution fut cependant moindre que celle qui a été vérifiée après mainpulation du cordon spermatique (37%). Les variations de l'APP furent toujours plus nettes que celles de la pression artérielle systolique et/ou que celles de la fréquence du pouls ($P < 0{,}05$). Les régressions linéaires et le test de Fisher ont montré que, pendant l'induction de l'anesthésie avec de l'halothane/70% N_2O au masque ($n = 6$), les variations de la concentration alvéolaire d'halothane correspondaient davantage aux variations de l'APP qu'aux variations de la pression artérielle systolique et/ou qu'aux variations de la fréquence du pouls ($P < 0{,}02$). En conclusion, la PPD informatisée permet de faire la distinction entre la réponse sympathique à l'incision de la peau et celle qui est reliée aux manipulations du cordon spermatique. Elle permet aussi de quantifier la réponse sympathique à l'anxiété pré-opératoire et, par conséquent, elle s'avère très utile pour quantifier le dégré de sédation pré-anesthésique.

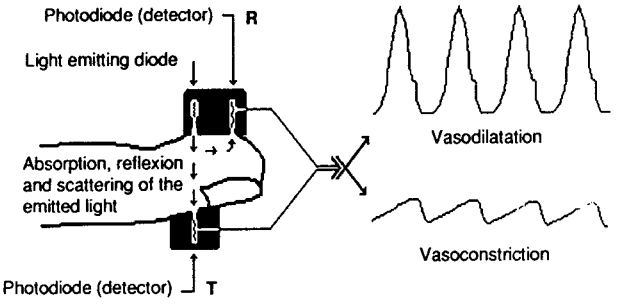

FIGURE 1 The photo-plethysmographic transducer: **R** = reflexion mode; **T** = transmission mode.

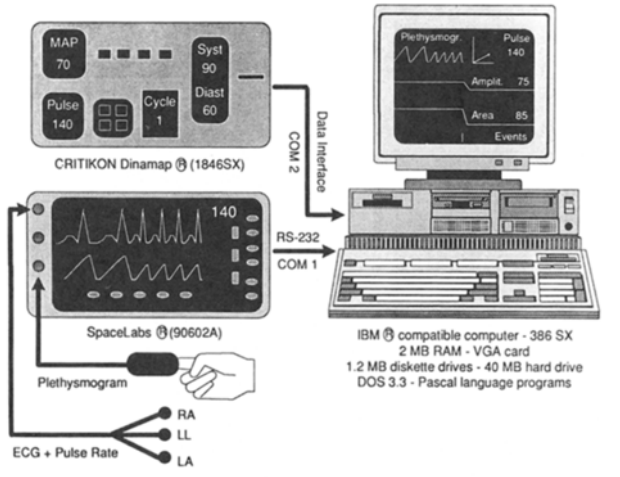

FIGURE 2 Configuration of the equipment for studying photoplethysmography of the finger.

Photo-plethysmography of the finger (PPF) was first described by Hertzman and Spealman (1937).[1] The basic principle of PPF is simple.[2-3] A small red/infrared light (660–940 nm) and a photo-sensitive detector are attached to a fingertip either in the reflexion or in the transmission mode (Figure 1). The emitted light is partly absorbed in the solid tissues (skin, connective tissue and bone), and in the circulating blood, as well as reflected by the erythrocytes and the vessel walls. Another part of the emitted light emerges through the skin and is sensed by the photodiode detector. This detected light pulsates synchronously with pulsations of the cutaneous vascular bed. Light pulsations are then electronically converted to amplified voltage pulsations corresponding to the heart beat. This pulsating AC signal is continuously displayed on an oscilloscope (Figure 2). Photo-plethysmography of the finger can be used during anaesthesia to monitor changes in the pulse rate and to detect haemodynamic disturbances.[3-4] Changes in the respiratory waves of the photoplethysmogram have clinical importance because an increase in the height of respiratory waves is a sign of relative hypovolaemia in patients receiving positive pressure ventilation.[3,5] When displayed continuously on an oscilloscope, PPF indicates electro-mechanical dissociation[6] and cardiac arrhythmias.[7] Furthermore, PPF can be used to detect the responses of the autonomic nervous system to stressful situations (mental effort, apprehension, fear, anxiety)[8-10] and nociceptive stimulation.[8,11] Finally, PPF may be used as an adjunct in Allen's test,[12,13] to evaluate sympathetic blockade and denervation of the extremities,[14-16] and to detect arterial vasospasm.[16-17] The device is non-invasive, and can be applied easily and rapidly in patients of any age.

Despite these advantages, PPF has not been applied universally. This may be for three main reasons: (1) unfamiliarity;[3] (2) difficulty in finding a numerical index and accurate system to measure the amplitude of the plethysmographic pulsations;[5] (3) tendency to forget the advantages of PPF and to consider it as a sub-product of pulse oximetry.

We have designed a microcomputer system to study PPF. The following report introduces automatic measurement of the photo-plethysmographic amplitude, evaluates whether or not PPF permits discrimination between two different surgical stimuli (skin incision, and manipulation of the spermatic cord) during halothane/70% nitrous oxide anaesthesia, and reviews the fundamental aspects and clinical applications of PPF.

Methods

The configuration of the equipment for studying PPF is shown in Figure 2. Programmes in Pascal language enable the acquisition, processing and analysis of data are outlined in Figure 3. Area measurements were discarded from the present study. The SpaceLabs® monitor (Model 90602A) delivers a digital plethysmogram in an arbitrary scale of 0–255 units (8 bits) at a rate of 56 Hz. The maximum value of this scale corresponds to $(2^{8\ bits}) - 1 = 255$ units. In our system, one unit represents 1/256 of the maximal upward or downward deflection, when the gain control of the SpaceLab® monitor is set at the sub-maximal level (level #3). The photo-plethysmographic transducer was attached to the left thumb at the optimal application pressure (i.e., the pressure enabling the highest plethysmographic tracing). Blood pressure measurements were recorded from the right arm. An *iv* cannula was inserted either in the right hand or in one foot, so that plethysmographic recording was not influenced by extraneous factors. The technical recommendations summarized in Table I were respected. The study was approved by The Committee on Medical Ethics, and informed consent was obtained from the parents. To evaluate discrimination between two different surgical stimuli we studied 50 non-premedicated boys, ASA physical status I, between one and ten years of age, who required outpatient inguinal hernia repair. The following previously calibrated monitors were used in all children: continuous ECG (CM-5), photo-plethysmograph, and rectal temperature (SpaceLabs® monitor Model 90602A); blood pressure measurements with an automatic cuff (Dimamap®; pulse oximeter, infrared spectroscopic analyzer of the end-tidal and inspired concentrations of halothane and CO_2 (Narkomed 4B®. Anaesthesia was induced with halothane, nitrous oxide and oxygen (30%) by mask. After intravenous atropine, 0.01 $mg \cdot kg^{-1}$, tracheal intubation was performed, without the use of muscle relaxants, under halothane (3.0–3.5% inspired; 2.8–2.9 end-tidal) in oxygen. Anaesthesia was then maintained with halothane (1.25–1.5% end-tidal) in a mixture of nitrous oxide and oxygen (FIO_2 = 0.3), and mechanically controlled ventilation was adjusted to maintain $PETCO_2$ at 32–38 mmHg (4.26–5 kPa), and peripheral oxygen saturation ≥ 98%. The rectal temperature was kept between 36.3 and 37°C (the ambient operating room temperature was kept between 20 and 21°C).

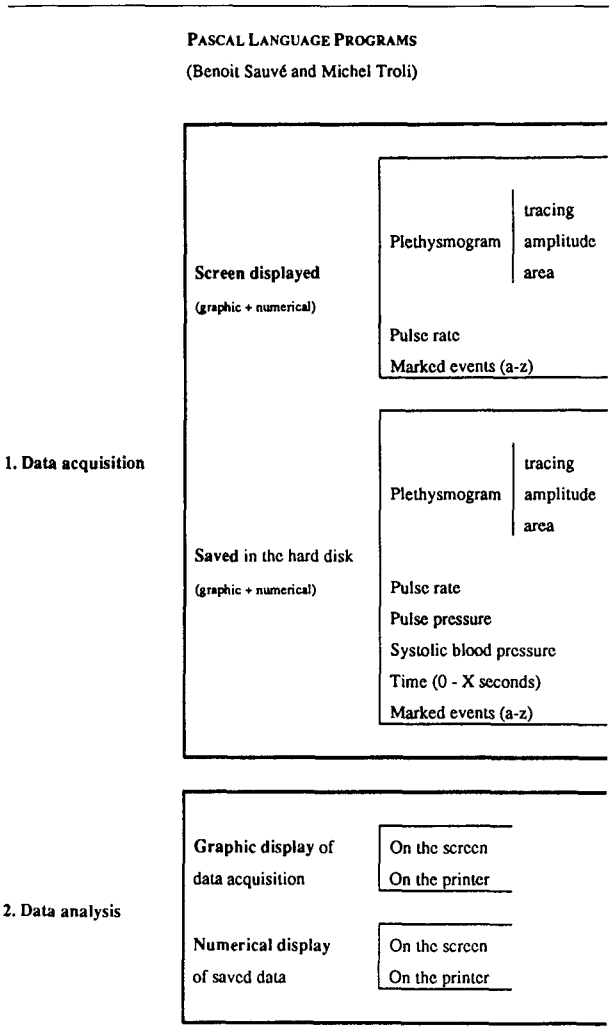

FIGURE 3 Outline of the options and functions available using Pascal language programmes. The plethysmogram tracing is displayed in real-time. Automatic estimations of the plethysmographic amplitude and area, as well as recording of other data, can be obtained every 15, 30, 60 or 90 sec, and/or "on demand."

The microcomputer was set to display and store data every 30 sec. The minima and maxima of the arterial pulsations were determined by the microcomputer by using iterative comparisons with the signal sent by the

TABLE I Problems and sources of error with photo-plethysmography of the finger

Problems and sources of error	*Recommended measures*
Cannot be calibrated	Each patient serves as his/her own control Standardize gain control at the same level. Attach transducer to the same finger (left thumb) at the optimal application pressure.* Keep transducer at the heart level. Keep the patient normothermic.
Individual variations in absorption, scattering and reflexion of the emitted light	Each patient serves as his/her own control. Standardize gain control at the same level. Attach transducer to the same finger (left thumb) at the optimal application pressure.* Keep transducer at the heart level. Keep the patient normothermic.
Contamination by ambient light	Cover the hand with an opaque blanket.
Sensitive to motion and/or pressure artifacts	Protect the hand with a stiff plastic cover.
Influenced by regional hypothermia	Cover the hand with an opaque blanket. Keep the patient normothermic.
Burns (neonates and small infants; hypotension, shock, intense peripheral vasoconstriction)	Attach transducer to another finger every hour; avoid photo-plethysmography of the finger.

*Optimal application pressure = pressure of about 40 mmHg (5.32 kPa) at which the amplitude of the photo-plethysmogram reaches its maximum (see Figure 6).

SpaceLabs® monitor (at a rate of 56 Hz). To insure that each computer sample included a full pulse wave, the pulse period (1/pulse rate) was calculated from the pulse rate (delivered by the monitor every two seconds) and the sampling time was extended to the pulse period plus 20%. This sampling time made it possible to compute the difference between the two extremes of a full arterial wave and minimized the effects of the slow respiratory waves. The mean value of three successive arterial amplitudes was considered as an approximation of the real amplitude of the arterial pulsations (recorded at the end of each 30 sec).

When end-tidal halothane (1.25–1.5%) and the plethysmographic tracing had been steady for at least five minutes, the surgeon proceeded to skin incision. The values of the photo-plethysmographic amplitude recorded immediately before the skin incision were later compared with the same values obtained by direct measurement of the plethysmographic tracing. For this purpose, we used the data analysis programme (Figure 3). The plethysmogram tracing was frozen immediately before the event marking out the skin incision. This frozen screen image was then printed on paper and manual (direct) readings of the plethysmographic amplitude were made by a non-blinded measurer, using a Digimatic® calliper (Mitutoyo Corporation, Model 500-321; resolution = 0.01 mm). The mean amplitude of three successive arterial waves was calculated. Each mean amplitude value was finally converted to the units scale using the factor of 6.22 (1 mm = 255 units/41 mm).

The values of the photo-plethysmographic amplitude, systolic blood pressure, and pulse rate recorded immediately before skin incision were later compared with the maximum changes in these same values recorded 30–90 sec after the skin incision, and 30–90 sec after manipulation (traction + dissection) of the spermatic cord.

Six boys (three to ten years old) stayed quiet enough, during induction of anaesthesia, to allow regression analysis of photo-plethysmographic amplitude, systolic blood pressure, and pulse rate (Y) on end-tidal halothane/70% nitrous oxide (X).

Comparisons between computerized and direct (manual) measurements were made using Spearman and Kendall's Tau rank correlations, the Kolmogorov-Smirnov two-samples test, regression analysis with ANOVA,[18] and the method proposed by Bland and Altman.[19] Changes related to anaesthesia induction, skin incision, and manipulation of the spermatic cord, were analyzed using regression analysis, Fisher's exact test (two-tailed), ANOVA for repeated measures followed by the Tukey multiple comparisons test, and Mann-Whitney rank-sum test (two-tailed) with the Bonferroni correction to make pairwise comparisons, where appropriate. A P value of < 0.05 was considered statistically significant.

Results

Demographic data (mean ± SD) were the following: age (yr) = 4.6 ± 2.7 (1–10); end-tidal halothane in 70% N_2O (%) = 1.3 ± 0.09 (1.25–1.5); end-tidal CO_2 (mmHg) = 34 ± 1.9 (32–38); SpO_2 (%) = 98.7 ± 0.7 (98–100); rectal temperature (°C) = 36.6 ± 0.17 (36.3–37).

The Spearman and Kendall correlations showed that computerized and direct estimations of the arterial wave amplitudes were associated ($P < 0.0001$). The Kolmogorov-Smirnov's test revealed that the two distributions were identical ($P = 1$). The prediction formula obtained from regression analysis (C = 0.396 + 1.0009 D) showed that computerized measurements (C) were 0.4

or less % higher than direct measurements (D) if direct estimations were ≥ 137 units (median), and did not exceed an 8% difference if the directly measured amplitudes were equal to five units. The mean difference between computerized and direct estimations of the photo-plethysmographic (arterial waves) amplitude was 0.52 ± 1.08 units, with 95% confidence interval 0.2 to 0.8. Thus, computerized estimations tended to give a higher reading by between 0.2 and 0.8 units. The limits of agreement (-1.6 and 2.6) were small enough, on a scale of 0–255 units, to be confident that computerized measurements can be used for clinical purposes.

Skin incision and manipulation of the spermatic cord caused decreased photo-plethysmographic amplitude and increased systolic blood pressure and pulse rate. These changes were more pronounced 30–90 sec after spermatic cord manipulation than 30–90 sec after skin incision ($P < 0.05$). Changes in photo-plethysmographic amplitude were always more evident than changes in pulse rate and systolic blood pressure (Figure 4). Linear regressions followed by the Fisher's exact test (two-tailed) showed that, during induction of anaesthesia with halothane in 70% N_2O (n = six boys), changes in end-tidal halothane concentration were related more to changes in photo-plethysmographic amplitude than to changes in systolic blood pressure and/or in pulse rate ($P < 0.05$).

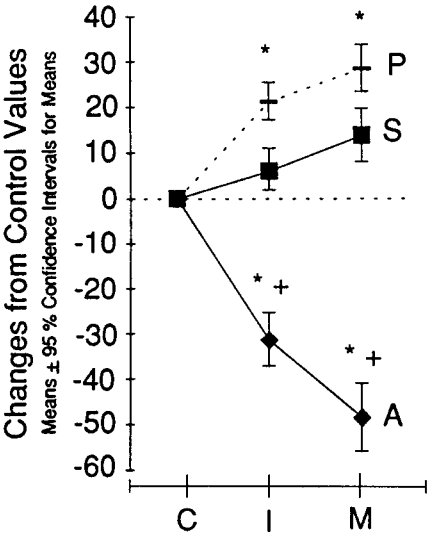

FIGURE 4 Changes in photo-plethysmographic amplitude (A = units), systolic blood pressure (S = mmHg), and pulse rate (P = beats · min^{-1}) from control values (C); I = 30–90 seconds after skin incision; M = 30–90 seconds after spermatic cord manipulation; * P < 0.05 vs S; + vs P (vertical comparisons). (Mann-Whitney rank-sum test – two-tailed – with the Bonferroni correction for two comparisons.)

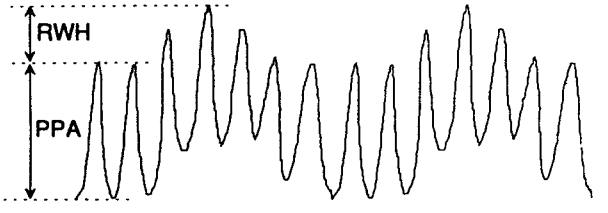

FIGURE 5 Photo-plethysmogram of the finger (drawing): PPA = Photo-plethysmographic (arterial wave) amplitude; RWH = respiratory wave height.

Discussion

The photo-plethysmographic tracing comprises two wave forms: (1) rapid or "arterial waves" synchronous with the heart beat; and (2) slower or "respiratory waves" caused by ventilation dependent changes in intrathoracic pressure[3,4,7] (Figure 5). During general anaesthesia, the amplitude of the rapid arterial waves is inversely related to the degree of sympathetic stimulation of the smooth muscle of the finger arterial bed.[3,5,11] Constriction of the blood vessels of the finger is the earliest sign of sympathetic activity in the human subject.[3,4,8,11,20] Nijboer and Dorlas showed that the photo-plethysmogram recorded from the finger is more sensitive to variations of sympathetic activity than that recorded from the pinna.[21] The amplitude of the slower respiratory waves is dependent on the intrathoracic pressure and central venous pressure.[3] Partridge showed that the amplitude (height) of the plethysmographic respiratory waves is inversely related with the central venous pressure in patients receiving general anaesthesia with positive pressure ventilation.[5]

Sluiter *et al.*[22] developed a peak detector which calculated the peak-to-peak amplitude of each arterial pulse wave and eliminated the slower ventilatory component. In our computerized system, algorithms have been developed to minimize the effect of ventilatory waves, to eliminate other spurious signals, and to calculate the amplitude of arterial waves. Hertzman reported a good correlation between PPF and blood flow on the finger[20] and Dorlas and Nijboer found no difference between changes in photo-plethysmographic and mercury-in-rubber strain-gauge plethysmographic amplitudes of adjacent fingers during general anaesthesia.[3]

Changes in PPF amplitude correspond to changes in the blood volume pulsations (ΔV) and depend on the distensibility of the vascular wall (D) as well as on the intravascular pulse pressure (ΔP). This relationship was formulated by Burton[23] as $\Delta V = D \cdot \Delta P$. Usually, the effect of autonomic impulses upon distensibility (D) is so strong that it completely predominates over the opposite effect of pulse pressure (ΔP). Decreases in PPF amplitude connected with pain and other stressful stimuli

are not accompanied by a decrease in pulse pressure (δP). Therefore, they have to be attributed to a decrease in distensibility (D) due to vasoconstriction of the finger arterial bed.[3] In other words, sympathetic stimulation is usually accompanied by decreased PPF amplitude and unchanged or increased pulse pressure. However, when digital vasodilatation reaches its maximum, D becomes a constant and then ΔV depends directly on ΔP. We have been using PPF since 1974 and have observed this phenomenon in neonates and small children. During general anaesthesia, a simultaneous decrease PPF amplitude and systolic blood pressure signifies deep anaesthesia (if the possibility of acute and severe hypovolaemia is excluded).

Why did we discard changes in arterial plethysmographic area while our experimental system allowed automatic estimation of this area (Figures 2 and 3)? First, because the area beneath the curve of one arterial wave represents the product of its mean amplitude by its period (1/pulse rate). In other words, changes in arterial plethysmographic area represent changes in arterial plethysmographic amplitude multiplied by changes in 1/pulse rate. Consequently, changes in arterial pulse area are more or less "amplified" by changes in pulse rate, and so exact comparisons between concomitant changes in the finger blood flow, pulse rate, and/or systolic blood pressure cannot be made. Second, our computerized system measures the area beneath the arterial curve by using the "trapezoidal rule"[24] and fixes the baseline of the curve at the zero units level. Consequently, our computerized system is probably less accurate when measuring the arterial pulse area than when computing the arterial wave amplitude. However, Sara and Shanks mention that the area beneath the curve of the pulse wave multiplied by the pulse rate represents the "perfusion index."[7]

It should be realized that PPF, as with any other form of monitoring, has limitations, drawbacks and sources of error (Table I). The major problem with PPF is that the total amount of light detected cannot be calibrated. Nevertheless, we can quantify changes in PPF amplitude when each patient serves as his/her own control and if we standardize the techniques of recording and measurement summarized in Table I. Dorlas and Nijboer emphasized that the amplitude of the plethysmogram reaches its maximum at an optimal application pressure of about 40 mmHg (5.32 kPa).[3] In order to adjust this application pressure we use a small rubber band over the plethysmographic probe (Figure 6). By changing the position of the rubber band we can change the application pressure until the amplitude of the plethysmogram reaches its maximum. Johnstone adjusted the application pressure with a screw.[11]

Lebowitz[25] reported two cases of thermal injury (one resulting in gangrene of the thumb), following the use

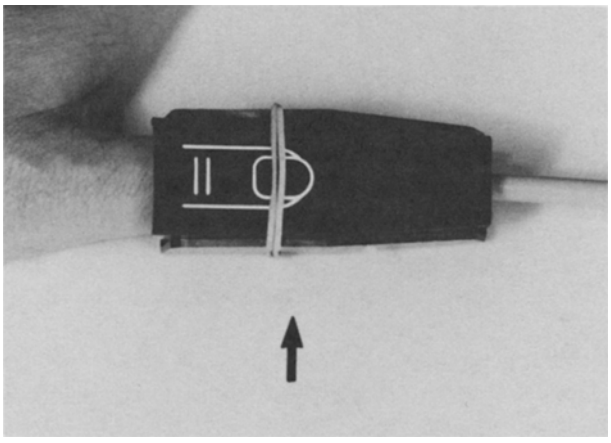

FIGURE 6 The photo-plethysmographic probe of the SpaceLabs Monitor® (Model 90602A) with a rubber band (arrow) to adjust the application pressure.

of PPF in a newborn and a small infant. Thus, in these small patients, as well as in people suffering from restrictive flow to the extremities, the risk/benefit of plethysmography (and/or of pulse oximetry) must be weighed on an individual basis. Even in normothermic and normovolaemic small patients, the plethysmogram (or pulse oximeter) transducer should be attached to a different finger every hour. If these patients become hypovolaemic with arterial hypotension and/or hypothermia (intense peripheral vasoconstriction) PPF (as well as pulse oximetry) is better avoided or discontinued.

Clinical anaesthetists are aware that peritoneal stimulation elicits a stronger sympathetic response than skin incision.[11] The present study showed that computerized photo-plethysmography of the finger (CPPF) allows quantification of the sympathetic response to different surgical stimuli. Surgical manipulation (traction + dissection) of the spermatic cord caused a greater reduction in photo-plethysmographic amplitude (37%) than skin incision (24%). Changes in photo-plethysmographic amplitude were more pronounced than changes in pulse rate and/or in systolic blood pressure (Figure 4).

Johnstone[9] reported that digital vasoconstriction was constantly observed in anxious non-premedicated patients (n = 50) awaiting the induction of anaesthesia (mean arterial plethysmographic amplitude = 2.1 mm; range = 1–5 mm). On the contrary, non-anxious controls (n = 100) presented a mean plethysmographic amplitude of 17.1 mm (range = 11–35 mm), and patients premedicated with haloperidol, 5 mg *im* one hour before induction of anaesthesia (n = 50), had a mean plethysmographic amplitude of 15.6 mm (10–19 mm) when

TABLE II Clinical applications of photo-plethysmography of the finger, a non-invasive monitor

Detection and/or evaluation of	*References*
Changes in pulse rate	3–4
Systolic blood pressure	5
Haemodynamic disturbances	3–5
Electro-mechanical dissociation	6
Cardiac arrhythmias	7
Stressful situations (mental effort, apprehension, fear, anxiety)	8–10, present study
The effectiveness of sedatives	9–10, present study
Nociceptive stimulation	3,8, present study
Arterial patency (and as an adjunct in the Allen's test	13
Arterial vasospasm	16–17
Sympathetic blockade and denervation of the extremities	14–16, 26–27
Changes in volaemia and central venous pression	3, 5
Peripheral replants and revascularizations	28
Steal syndrome following arterio-venous fistulas and shunts	29

awaiting induction of anaesthesia. Johnstone concluded that PPF provides objective evidence of the presence of anxiety.[9] Chambiras[10] reported that diazepam, 2 mg *iv*, caused a rapid onset of vasodilatation, followed by drowsiness, slurred speech, and lowering or drooping of the eyelids, in 30 patients awaiting dental repair in an ambient room temperature of 20–22°C (68–72°F). Dorlas and Nijboer found that, during anaesthesia, the decrease in plethysmographic amplitude always preceded the decrease in finger temperature and concluded that the decrease in temperature is the result of and not the reason for, the vasoconstriction.[3] Consequently, it seems reasonable to assume that, in the present series, pre-anaesthetic digital vasoconstriction and reduced PPF amplitude (often <40 units, eventually as low as 5 units) was related to apprehension and/or anxiety. Indeed, we verified that, in six children who stayed quiet during induction of anaesthesia with halothane in 70% N_2O by mask, the PPF amplitude increased linearly with the alveolar concentrations of halothane. In contradistinction to the photo-plethysmographic amplitude, systolic blood pressure and pulse rate did not always fit the linear regression model ($Y = a + b\ X$) with increasing alveolar concentrations of halothane. This seems to corroborate the reports by Johnstone[9] and Chambiras[10] who recommend PPF to evaluate the sympathetic response to anxiety, and to study the efficacy of sedatives. Clinical applications of PPF are summarized in Table II.

It is important to recognize that, unfortunately, some pulse oximeters display a misleading "plethysmogram." When a small pulsating absorbance signal is detected (digital vasoconstriction = low AC-to-DC signal ratio), the pulse oximeter rapidly amplifies the signal and estimates saturation from the ratio of the amplified absorbances.[30] If this amplification is transmitted to an oscilloscope and/or to a printer, it becomes impossible to detect changes in the PPF amplitude. Computerized PPF is likely to become popular if it becomes available as part of pulse oximetry. A "new and complete pulse monitor," including the advantages of pulse oximetry and computerized PPF, with a single plethysmographic probe, could be a useful clinical monitor.

In conclusion, computerized estimations of plethysmographic (arterial waves) amplitude are accurate enough for clinical purposes provided that the recommendations indicated in Table I are carefully followed. Computerized photo-plethysmography of the finger (CPPF) allows quantification of the sympathetic response to apprehension, fear and/or anxiety, and to different surgical stimuli. We feel that it has the potential to be a valuable non-invasive tool for monitoring the response of anaesthetized patients in a wide variety of clinical situations. We hope that manufacturers of anaesthetic monitors will consider inclusion of CPPF in pulse oximeters.

Acknowledgements

We thank Mr. Claude Galand (Chief, Department of Biomedical Engineering, Hôpital Sainte-Justine) and all the members of his department for their collaboration and support. Also, we extend a note of appreciation to the surgeons, nurses of the operating room, anaesthesia and inhalotherapy staff, for their cooperation.

References

1 *Hertzman AB, Spealman CR.* Observations on the finger volume pulse recorded photo-electrically. Am J Physiol 1937; 119: 334–5.

2 *Hertzman AB.* The blood supply of various skin areas as estimated by the photoelectric plethysmograph. Am J Physiol 1938; 124: 328–40.

3 *Dorlas JC, Nijboer JA.* Photo-electric plethysmography as a monitoring device in anaesthesia: application and interpretation. Br J Anaesth 1985; 57: 524–30.

4 *Foster AD, Neumann C, Rovenstine EA.* Peripheral circulation during anesthesia, shock and hemorrhage; the digital plethysmograph as a clinical guide. Anesthesiology 1945; 6: 246–57.

5 *Partridge BL, Sanford TJ.* Finger plethysmography in anesthesia. Seminars in Anesthesia 1989; 8: 102–11.

6 *Kleine JW, Dorlas JC, Moesker A.* Anaesthesie bei Pacemakerimplatationen. Anaesthesist 1972; 21: 513–4.

7 *Sara CA, Shanks CA.* The peripheral pulse monitor – a review of electrical plethysmography. Anaesth Intensive Care 1978; 6: 226–33.

8 *Kumazawa T, Kobayashi M, Takagi K.* A plethysmographic study of the human skin under various environmental conditions. Jap J Physiol 1964; 14: 354–64.
9 *Johnstone M.* The effects of sedation on the digital plethysmogram. A radiotelemetric study of haloperidol. Anaesthesia 1967; 22: 3–15.
10 *Chambiras PG.* Evaluation of sedatives in dental practice. Preliminary report. Aust Dental J 1970; 15: 112–8.
11 *Johnstone M.* Digital vasodilatation: a sign of anaesthesia. Br J Anaesth 1974; 46: 414–9.
12 *Allen EV.* Thromboangiitis obliterans: methods of diagnosis of chronic occlusive arterial lesions distal to the wrist with illustrative cases. Am J Med Sci 1929; 178: 237–44.
13 *Brodsky JB.* A simple method to determine patency of the ulnar artery intraoperatively, prior to radial-artery cannulation. Anesthesiology 1975; 42: 626–7.
14 *Beene TK, Eggers GWN.* Use of the pulse monitor for determining sympathetic block of the arm. Anesthesiology 1974; 40: 412–4.
15 *Eastwood D.* Finger block for local vasodilatation – current comment. Anesthesiology 1959; 20: 704.
16 *Hertzman AB, Dillon JB.* Applications of photoelectric plethysmography in peripheral vascular disease. Am Heart J 1940; 20: 750–61.
17 *Kovac A, Smulewicz JJ.* The use of the pulse monitor in retrograde arteriography. Angiology 1969; 20: 483–7.
18 *Kleinbaum DG, Kupper LL, Muller KE.* Applied Regression Analysis and Other Multivariable Methods, 2nd ed., Boston: PWS – Kent Publishing Company 1988.
19 *Bland JM, Altman DG.* Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986; 1: 307–10.
20 *Hertzman AB.* Vasomotor regulation of cutaneous circulation. Physiol Rev 1959; 39: 280–306.
21 *Nijboer JA, Dorlas JC.* Comparison of plethysmograms taken from finger and pinna during anaesthesia. Br J Anaesth 1985; 57: 531–4.
22 *Sluiter ER, Rowaan CJ, Dorlas JC, et al.* Peak-to-peak detector for the arterial pulsations in the plethysmogram. II – Results of its use during anaesthesia. Med Biol Eng Comput 1981; 19: 267–70.
23 *Burton AC.* Physiology and Biophysics of the Circulation. An Introductory Text, 2nd ed., Chicago: Year Book Medical Publish Inc 1972.
24 *Thomas GB Jr, Finney RL.* Calculus and Analytic Geometry, 7th ed., New York: Addison-Wesley Publishing Company 1988; 290–5.
25 *Lebowitz MH.* Gangrene of the thumb following the use of the photoelectric plethysmograph during anesthesia. Anesthesiology 1970; 32: 164–7.
26 *Kim JM, LaSalle AD, Parmley RT.* Sympathetic recovery following lumbar epidural and spinal anesthesia. Anesth Analg 1977; 56: 352–5.
27 *Kim JM, Arakawa K, VonLintel T.* Use of the pulse-wave monitor as a measurement of diagnostic sympathetic block and of surgical sympathectomy. Anesth Analg 1975; 54: 289–96.
28 *Manke DA, Sumner DS, vanBeek AL et al.* Hemodynamic studies of digital and extremity replants and revascularizations. Surgery 1980; 88: 445–52.
29 *Dallay P, Brantigan CO.* Plethysmography and the diagnosis of the steal syndrome following placement of arteriovenous fistulas and shunts for hemodialysis access. J Cardiovasc Surg 1987; 28: 200–3.
30 *Tremper KK, Barker SJ.* Fundamental Principles of Monitoring Instrumentation. *In:* Miller RD (Ed.). Anesthesia, 3rd ed., New York: Churchill Livingstone 1990; 986–9.